Production of spherical super-heavy nuclei

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Introduction

Since GSI started its research program on super-heavy elements in the 1970s, an extensive program has continuously been carried out to explore the physics involved in the different processes which are relevant for the synthesis of the heaviest nuclei. Special emphasis was put on those features which are particularly relevant for reaching the next doubly magic spherical shell closure beyond ^{208}Pb. This long-term research program included several aspects, reaching from the amalgamation process of projectile and target nuclei under the influence of the strong repulsive Coulomb force up to the cooling down of the compound nucleus by particle evaporation in competition with a strong fission branch. It was decided to perform the necessary elaborate investigations by studying the synthesis of proton-rich nuclei near the 126-neutron shell, whose formation can be considered as a realistic test case for the production of spherical super-heavy nuclei. The common features are the spherical shape of the nuclear ground state and a large shell effect of more than 5 MeV. The larger liquid-drop component of the fission barrier of a few MeV ensures sizeable formation cross sections, which are a pre-requisite for systematic studies.

Entrance channel

Specific features of the entrance channel arise in the synthesis of spherical super-heavy nuclei, because the projectile-target combinations available on the basis of primordial nuclei require rather mass-symmetric systems, which consequently experience a very strong Coulomb repulsion in the amalgamation phase. The most extensive exploration of entrance-channel effects in fusion of massive systems, extending from ^{90}Zr + ^{90}Zr to ^{110}Mo + ^{110}Mo, is documented in Ref. [1]. These experiments revealed the onset of a considerable reduction of the fusion probability near the potential barrier already for symmetric systems with Z_1*Z_2=1600. This hindrance was related to the "extra-push" phenomenon, postulated by W. Swiatecki. More massive systems showed a stronger fusion hindrance and a more gradual increase of the fusion probability as a function of bombarding energy. The gradual increase of the fusion probability was interpreted as an evidence for strong fluctuations connected with the extra push. The nuclear-structure properties of projectile and target were found to have a decisive influence on this phenomenon: Projectile-target combinations with nuclei close to major shells were less affected. Some new experiments performed in other laboratories shed new light on these results. H. Ikezoe *et al*. have shown that the fusion probability of a deformed projectile or target nuclei can be understood by variations in the orientation of the colliding nuclei [2]. Tip-on-tip configurations lead to less compact contact configurations and experience a stronger extra-push in contrast to side-on-side collisions. In another very important work, Hinde *et al*. completed the series of projectile-target combinations leading to the compound nucleus ^{220}Th studied in [1] by the system ^{16}O + ^{204}Pb [3]. They obtained the surprising result that already the system ^{40}Ar + ^{174}Hf, which was considered previously to fuse in the lower angular-momentum range with high probability, experiences a strong fusion hindrance. On the basis of this new result, the systematics of fusion probabilities deduced in ref. [1] is to be revised. As a general conclusion, the extra-push phenomenon is found to set in for considerably lighter systems than previously known.

Exit channel

The exit channel in the synthesis of spherical super-heavy nuclei is subject to very specific features, which may differ considerably from those met in the production of deformed super-heavy nuclei. In the de-excitation of slightly excited highly fissile nuclei, nuclear-structure phenomena are expected to govern the competition between particle evaporation and fission due to the influence of shell effects and collective properties on the level density. Therefore, any extrapolation based on the experience in the synthesis of the heaviest nuclei reached up to now is highly doubtful. Again, extended studies on the synthesis of proton-rich nuclei near the 126-neutron shell were chosen as the appropriate tools to explore the features of the exit channel in the production of spherical super-heavy nuclei.

The results of a first experimental program, based on the production of a series of compound nuclei around the 126-neutron shell by heavy-ion fusion reactions, are documented in ref. [1]. It was found that the strong ground-state shell effect of these nuclei does not enhance the survival probability of the fused system against fission, although it is responsible for about half the height of the fission barrier.

In order to avoid the influence of fusion hindrance on these results, the fission competition of these nuclei was studied recently with a different experimental approach. The nuclei of interest were produced as secondary beams. They were excited by electromagnetic interactions to states of low angular momentum at energies only slightly above the fission barrier, and the cross sections for consecutive fission were measured [4]. Even at these low excitation energies no influence of the 126-neutron shell on the fission probability was observed.

A third approach exploited the production of proton-rich nuclei near the 126-neutron shell by bombarding copper, hydrogen and deuterium nuclei with ^{238}U at 1 A GeV [5-7]. In these reactions, a field of nuclides slightly lighter than the projectile are produced with excitation energies extending to several hundred MeV or more. The production of these prefragments is certainly not influenced by nuclear-structure properties. Only in the last steps of the deexcitation process an eventual influence of the 126-neutron shell on the fission competition is expected, which would lead to a structure in the nuclide distribution observed. Since the spallation process produces a large field of nuclei with comparable cross sections, it is well suited to reveal a possible enhancement of the survival probability of nuclei near N=126 in the deexcitation process by the appearance of a ridge which would be superimposed on the broad distribution of nuclide cross sections formed by the spallation process. The results of this approach also agreed with those found in our preceding experiments: The large ground-state shell effect of N=126 nuclei does not lead to a noticeable enhancement of the survival probability against fission in the deexcitation process.

These findings have been traced back to the specific features of the level densities of magic spherical nuclei [4,5]. While the number of intrinsic excitations is influenced by the sequence of single-particle energies, which would strongly enhance particle emission with respect to fission, the spherical nuclear shape only allows for collective excitations of vibrational character. Compared to the large number of rotational levels found at the fission-barrier deformation, this leads to strong enhancement of fission. It seems that these two counteracting structural effects cancel to a great extent in the case of proton-rich N=126 nuclei. As a consequence for the production of spherical super-heavy nuclei, we expect qualitatively a similar effect. Therefore, we expect that the systematics of production cross sections found in the synthesis of deformed super-heavy nuclei cannot be extrapolated for estimating the production cross sections of spherical super-heavy nuclei. Instead, one will probably face a considerably stronger decrease in the formation cross sections in the transition from the deformed to the spherical super-heavy region.

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